Univ. of Southern Cal.
LA

Final Technical Report

NASA Research Grant -1-471

"Evaluation of a Pulse Control Law for Flexible Spacecraft"

Reporting Period: 1 June 1984 - 31 May 1985

The past year has been devoted to a feasibility study, to the investigation of the pulse control technique developed by the PIs in vibration suppression in aerospace structures. The funding level precluded a study of a full-scale SCOLE model. Since the feasibility study results are strongly positive, it is hoped that additional funding will make it possible to extend the work to the SCOLE configuration during the coming year. Specifically, the following analytical and experimental studies were conducted:

(1) A simple algorithm was developed to suppress the structural vibrations of 3-dimensional distributed parameter systems, subjected to interface motion and/or directly applied forces. The algorithm is designed to cope with structural oscillations superposed on top of rigid-body motion: a situation identical to that encountered by the SCOLE components. A significant feature of the method is that only local measurements of the structural displacements and velocities relative to the moving frame of reference are needed; no global information about the stuctural characteristics of the oscillating system is needed. It was shown analytically that the algorithm guarantees stable motion.

(2) A numerical simulation study was conducted on a simple linear finite element model of a cantilevered plate wich was subjected to test excitations consisting of impulsive base motion and of nonstationary wide-band random excitation applied at its root. In each situation, the aim was to suppress the vibrations of the plate relative to the moving base. The influence of the following parameters on the efficiency of the vibration suppression techniques was evaluated:

(a) the total number of controllers
(b) the spatial distribution of the controllers
(c) the nature of the control pulse (e.g., active Coulomb damping, viscous, quadratic, etc.)
(d) duration of the control pulses
(e) minimum spacing of control pulses
(f) nature of the exciation, and
(g) control energy optimization

(3) A small mechanical model resembling an aircraft wing was designed and fabricated to investigate the control algorithm under realistic laboratory conditions. The wing was clamped to the top of an electrodynamic shaker made to oscillate in a prescribed form. The sensor consisted of piezoelectric accelermoters and optical displacement followers. A pneumatic power supply was used to energize the control thrusters which generated active Coulomb-type control forces by using mass ejection techniques in conjunction with solenoid-controlled nozzles. Inspite of the rudimentary nature of the experiment, a considerable amount of data was accumulated to validate the effectiveness and robustness of the proposed vibration control method.

(NASA-CR-176233) EVALUATION OF A PULSE CONTROL LAW FOR FLEXIBLE SPACECRAFT Final Technical Report, 1 Jun. 1984 - 31 May 1985 (University of Southern California) 40 p HC A03/MF A01 CSCL 22B G3/18

N86-10272

Unclas 15817

During the period 6-7 December 1984, one of the PIs (R.K. Miller) participated in the First SCOLE Workshop Concerning the NASA/IEEE Design Challenge and he presented a detailed report covering the analytical and experimental studies discussed above.

For convenience, the Appendix contains a copy of the transparencies that summarize our accomplishments during the first year of our NASA contract.

APPENDIX

EVALUATION OF ON-LINE PULSE CONTROL FOR VIBRATION SUPPRESSION IN FLEXIBLE SPACECRAFT

by

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Presented At

The First SCOLE Workshop Concerning the NASA/IEEE Design Challenge
Langley Research Center
Hampton, Virginia
6-7 December 1984

OUTLINE

1. Introduction
   The Pulse Control Strategy

2. Analytical Studies
   Stability Analysis, Digital Simulations

3. Analog Studies
   D/A, A/D Conversions, Analog Simulations

4. Experimental Studies

INTRODUCTION

Many active on-line optimal control strategies require:

* Accurate and complete mathematical models of the structure to be controlled

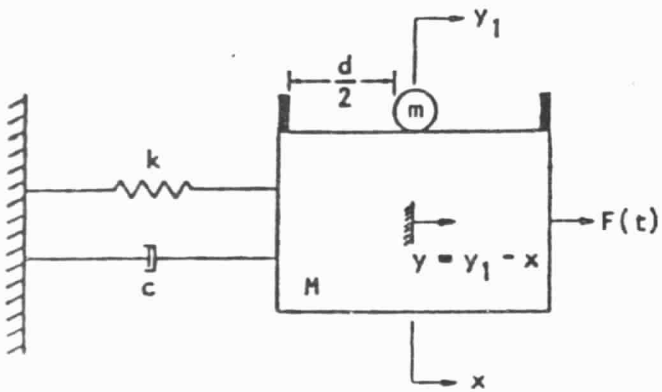
* Continuous monitoring (or estimation) of all the state variables

* Generation of continous control forces

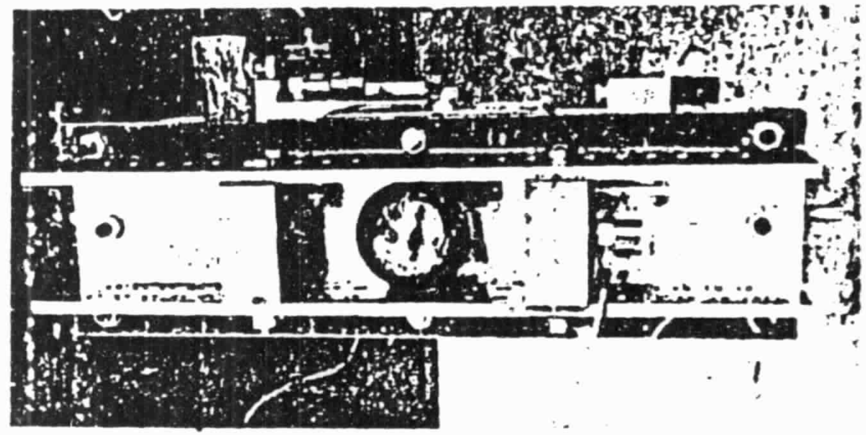
* Extensive on-line calculations

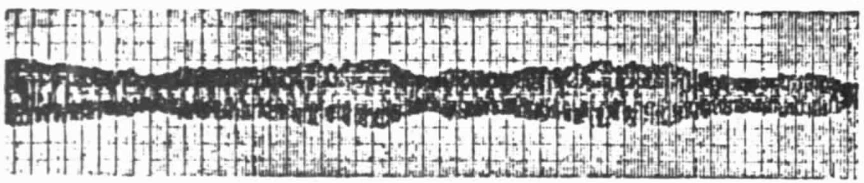
OUR PULSE CONTROL STRATEGY AVOIDS EACH OF THESE REQUIREMENTS

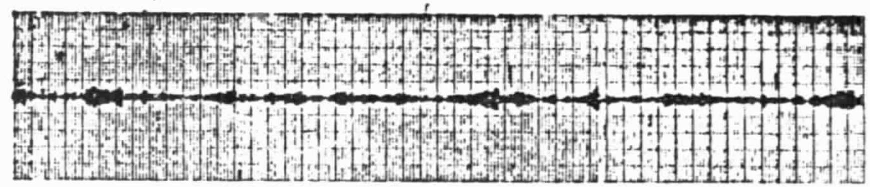
EVALUATION OF ON-LINE PULSE CONTROL FOR VIBRATION SUPPRESSION IN FLEXIBLE SPACECRAFT



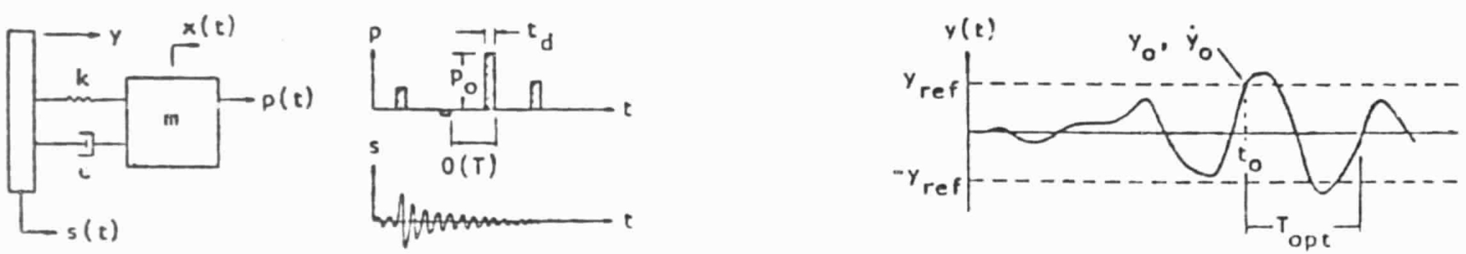
(a) Mathematical model


(b) Mechanical model


(c) Motion without damper


(d) Motion with impact damper

IMPACT VIBRATION DAMPER WITH RANDOM EXCITATION



EQUIVALENT SDOF SYSTEM TO BE CONTROLLED

ANALYTICAL STUDIES

Method 1 – Optimal Pulse Control of Linear Structures

* $M \ddot{\underset{\sim}{y}} + C \dot{\underset{\sim}{y}} + K \underset{\sim}{y} = \underset{\sim}{F}(t)$; $\underset{\sim}{y}(t)$; $\underset{\sim}{y}(t)$ Continuously available

* $\underset{\sim}{p}(t) = \underset{\sim}{p}\; p_0(t)$.......simultaneous control pulses

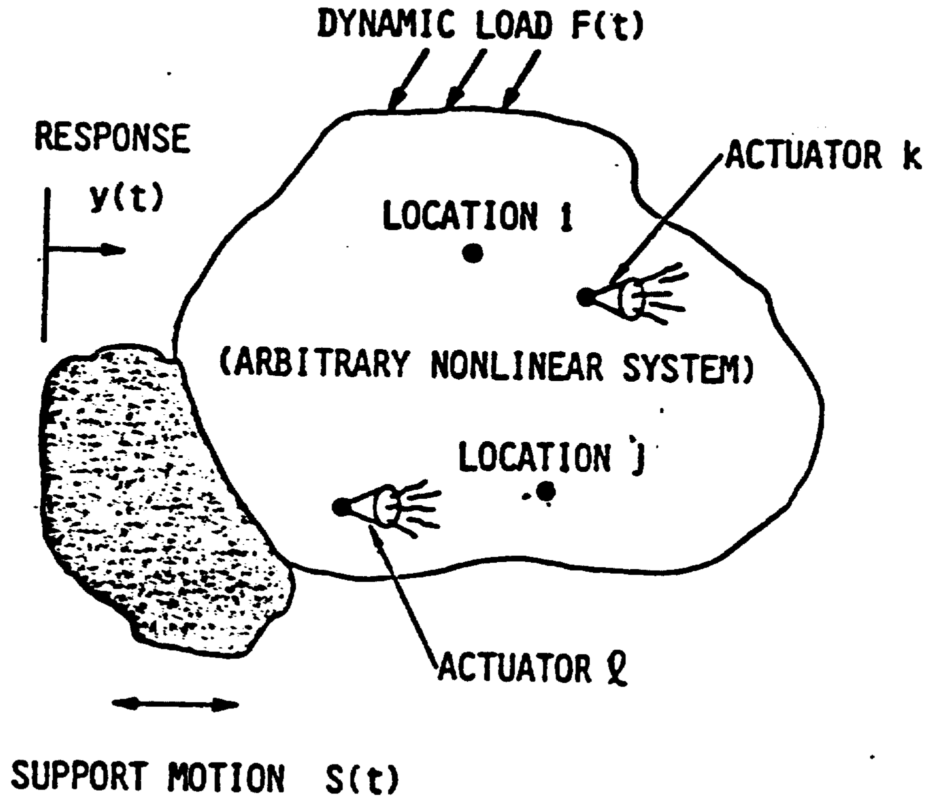
* Pulses activated upon threshold crossing (open loop)

* Minimum spacing between pulses is T_1, first natural period

* p chosen to minimize cost function

$$J(\underset{\sim}{p}) = E\left[\int_{t_o}^{t_o+\tau} \{\underset{\sim}{y}^T(t)\, w_1\, \underset{\sim}{y}(t) + \dot{\underset{\sim}{y}}^T(t)\, w_2\, \dot{\underset{\sim}{y}}(t)\}dt\right]$$

EVALUATION OF ON-LINE PULSE CONTROL FOR VIBRATION SUPPRESSION IN FLEXIBLE SPACECRAFT



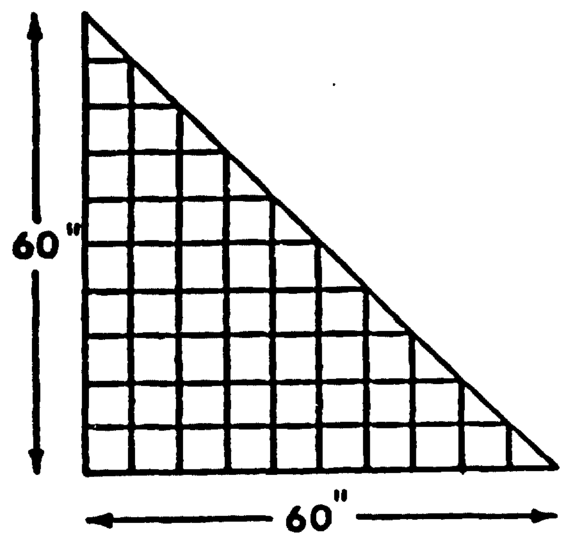
MODEL OF ARBITRARY NONLINEAR DISTRIBUTED PARMETER SYSTEM TO BE ACTIVELY CONTROLLED

Method 2 - Sub-Optimal Pulse Control of Nonlinear Structures

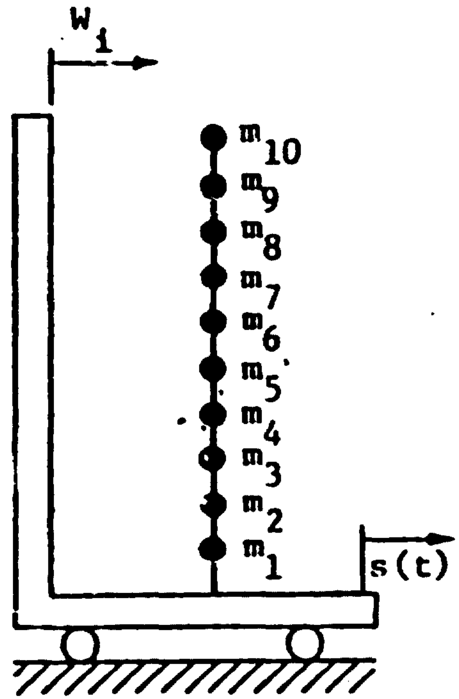
* Pulses triggered independently, at peak velocity (local)

* Pulse magnitude at each actuator location

$$P_i(t) = \begin{cases} -\gamma_i \ \mathrm{sgn}\,(\dot{y}_i)\,|y_i|^{n_i} & t_{0_i} \le t \le (t_{0_i} + T_{d_i}) \\ 0 & t > t_{0_i} + T_{d_i} \end{cases}$$



(a) plate properties



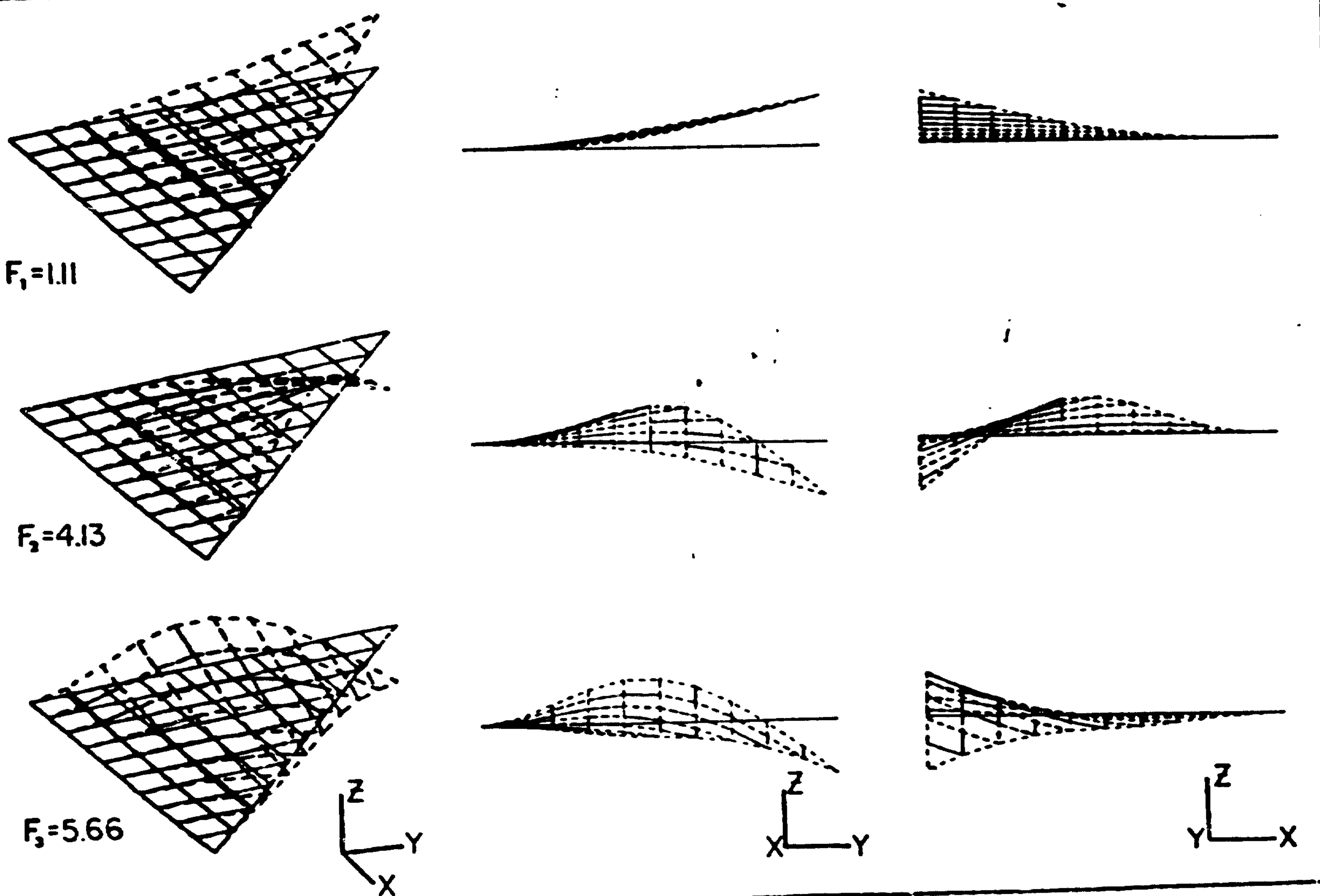
(b) discrete model

m_i	k_i	c_i
3.860D-03	3.745D+00	4.810D-03
3.454D-03	3.351D+00	4.303D-03
3.048D-03	2.957D+00	3.797D-03
2.641D-03	2.563D+00	3.291D-03
2.235D-03	2.168D+00	2.785D-03
1.829D-03	1.774D+00	2.278D-03
1.422D-03	1.380D+00	1.772D-03
1.016D-03	9.856D-01	1.266D-03
6.095D-04	5.914D-01	7.594D-04
2.032D-04	1.971D-01	2.531D-04

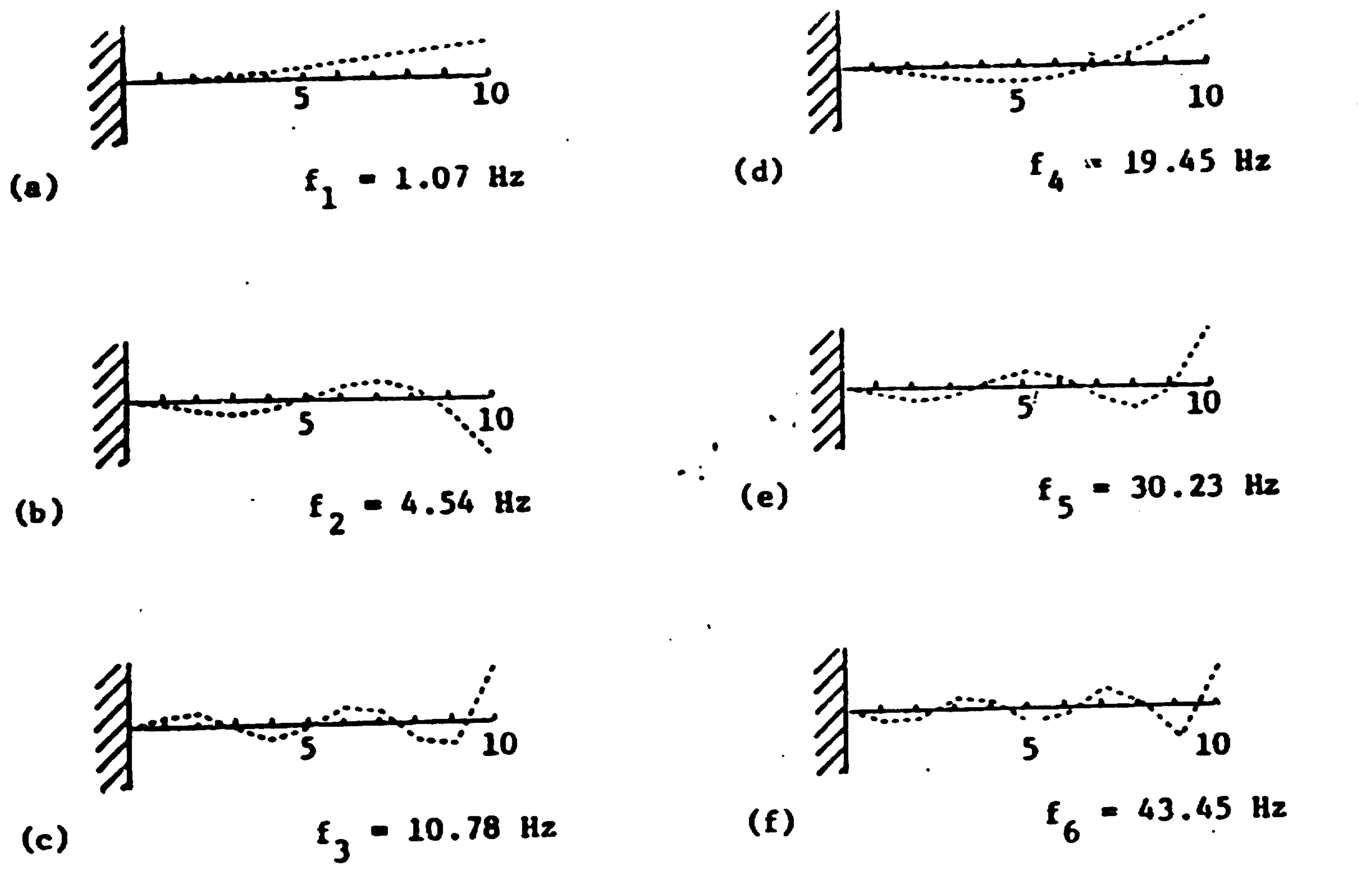
(c) linear system characteristics

Ten-degree-of-freedom model of cantilever plate

"Mode Shapes of the Flexible Appendage"

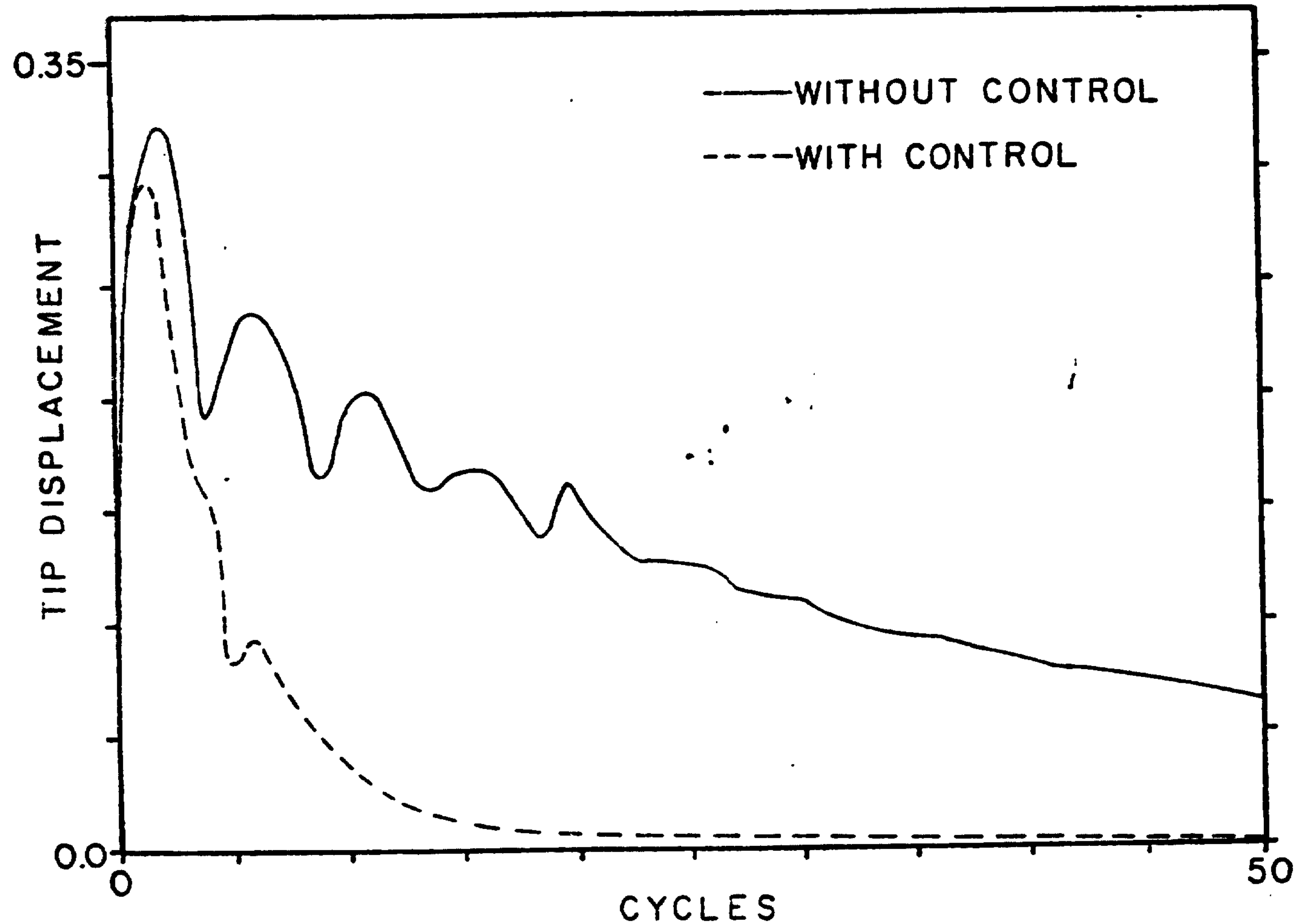


EVALUATION OF ON-LINE PULSE CONTROL FOR VIBRATION SUPPRESSION IN FLEXIBLE SPACECRAFT

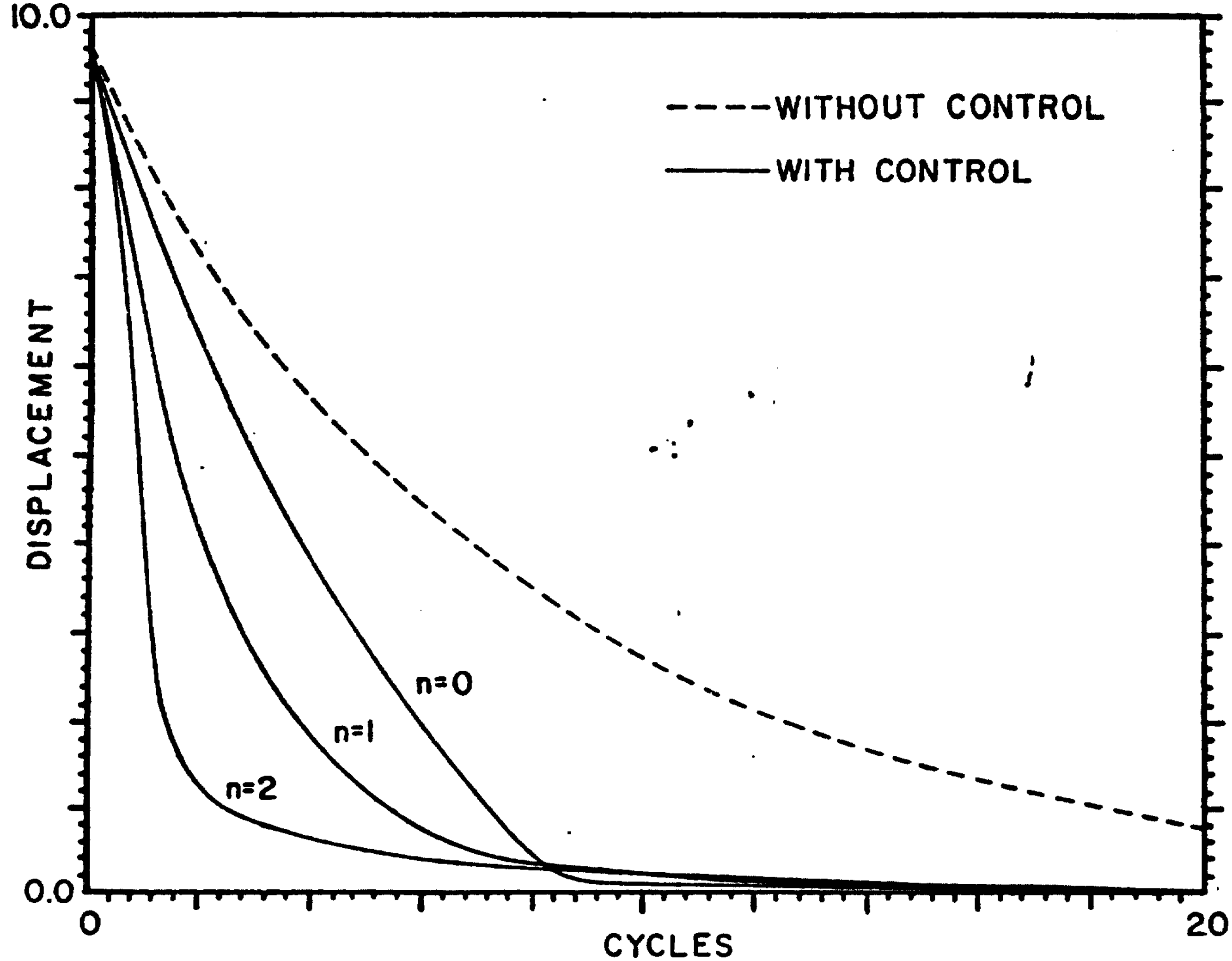


Dominant modal shapes of 10 DOF plate model

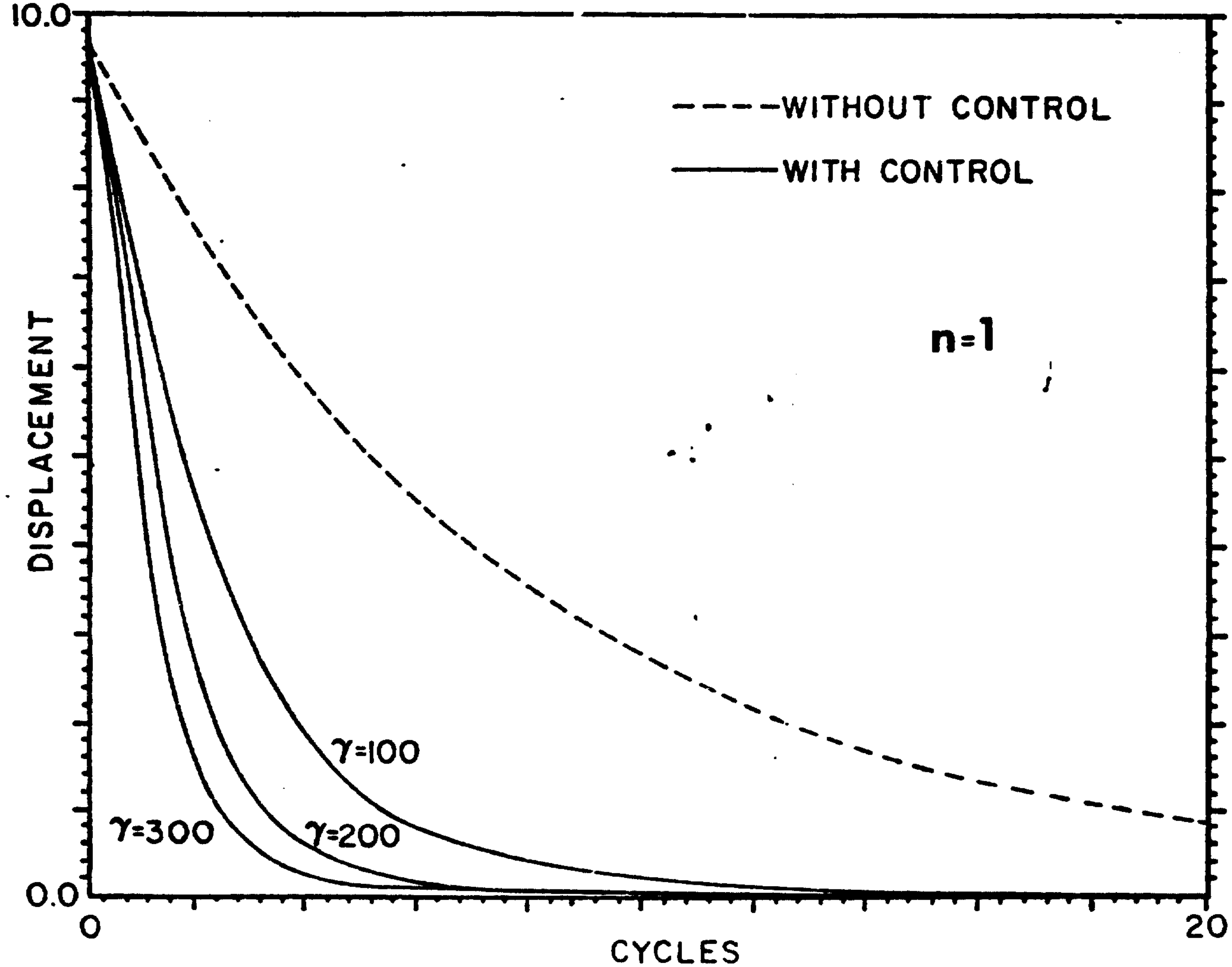
"Response of the Flexiable Appendage to Base Impact"



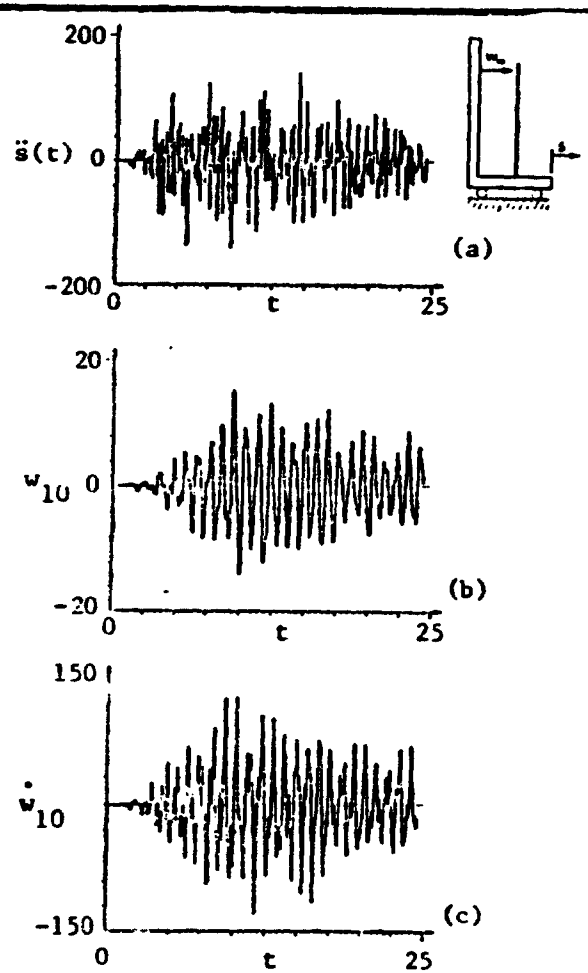
"Effects of Control Parameters"



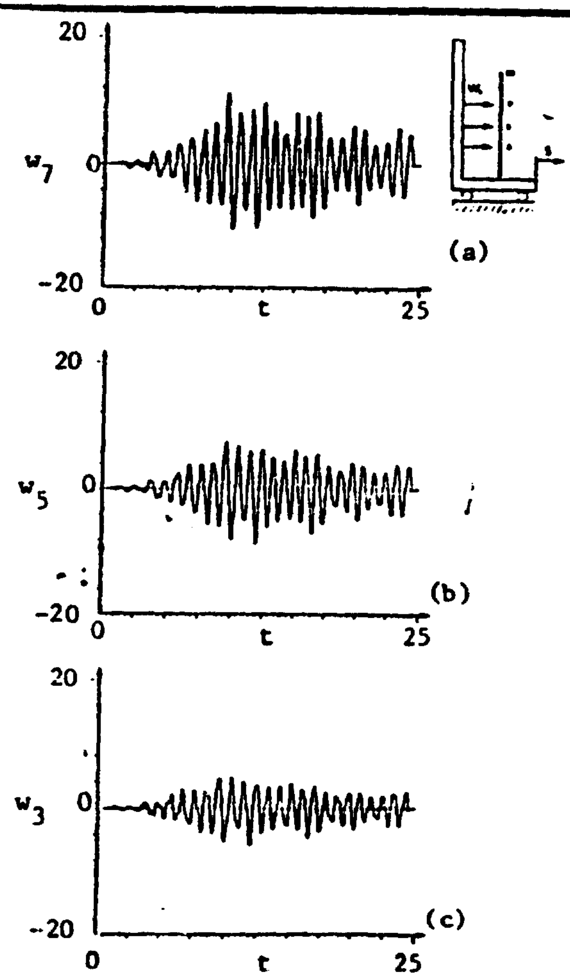
"Effects of Control Parameters"



EVALUATION OF ON-LINE PULSE CONTROL FOR VIBRATION SUPPRESSION IN FLEXIBLE SPACECRAFT

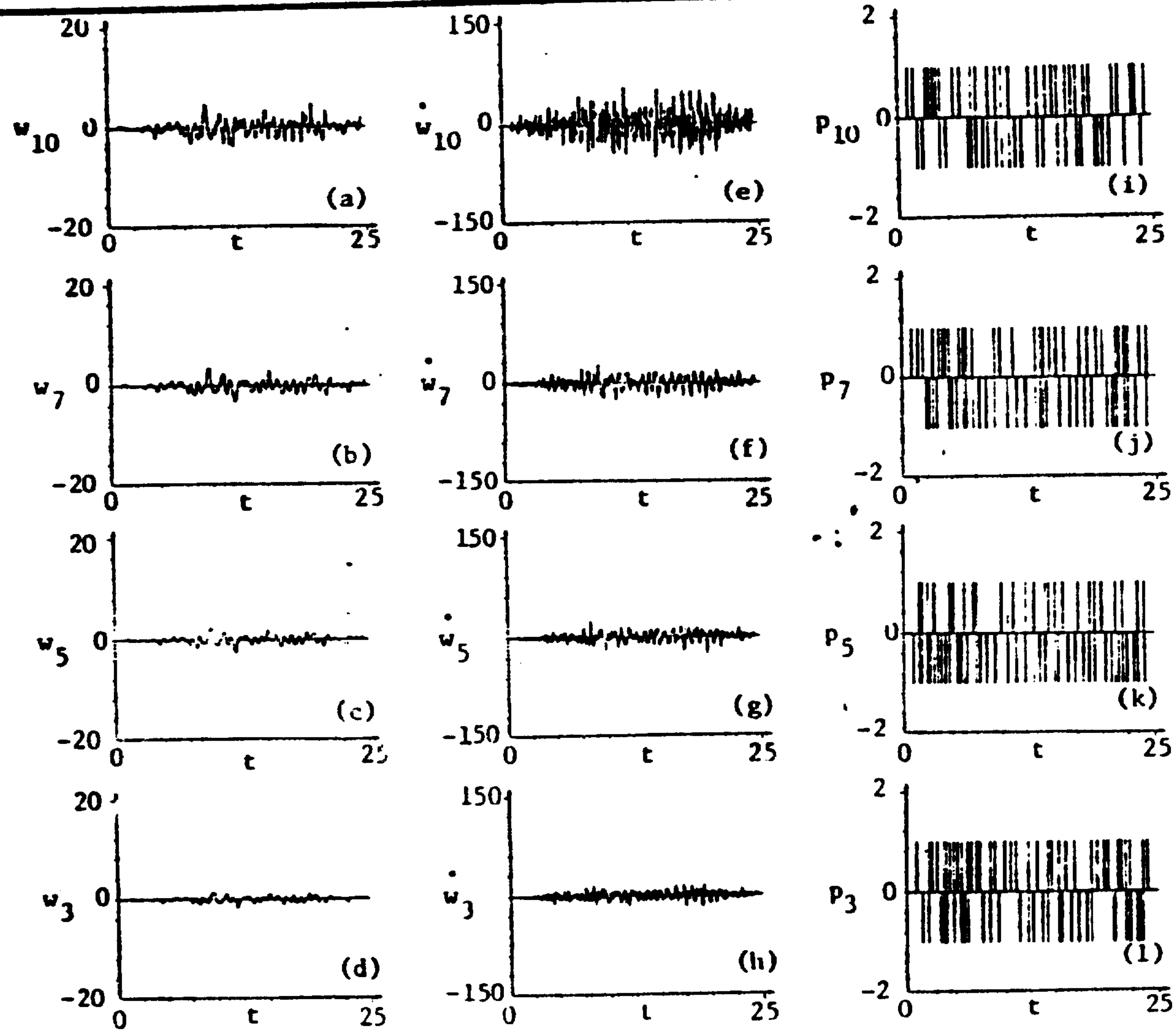


Uncontrolled motion of 10 DOF linear plate model under nonstationary base excitation.



Response time history at 3 locations along the uncontrolled 10 DOF linear plate model under nonstationary base excitation.

EVALUATION OF ON-LINE PULSE CONTROL FOR VIBRATION SUPPRESSION IN FLEXIBLE SPACECRAFT



Control parameters:

$n = 0$

$\bar{c} = 1$

$T_d = 0.05$

$T_{min} = 0.2$

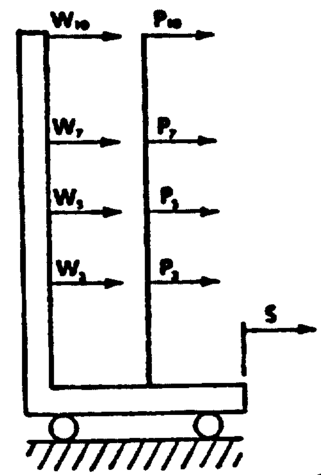


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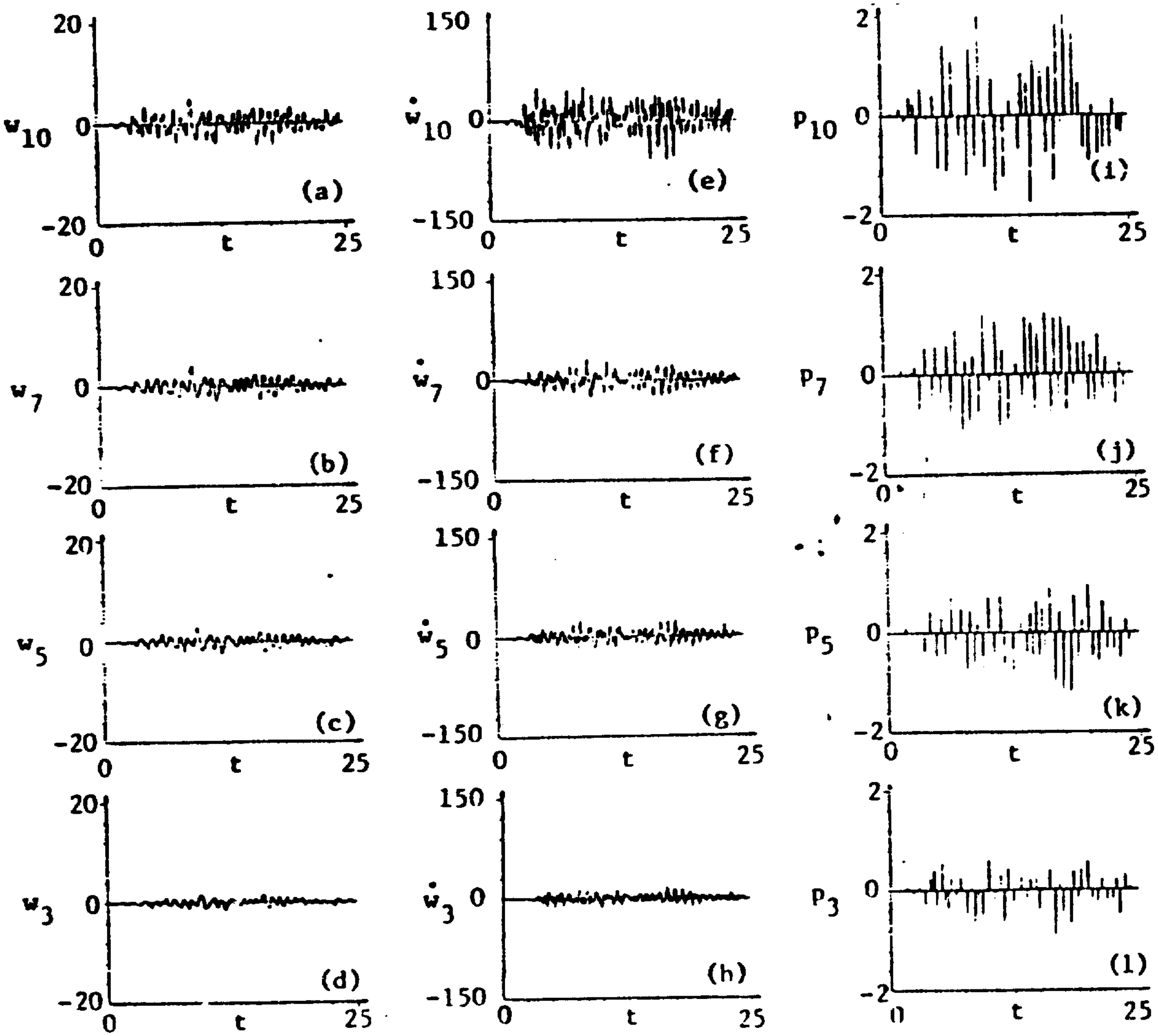
Figure 7. Controlled motion of the 10 DOF linear plate model under nonstationary base excitation; 4 identical controllers used at locations m_3, m_5, m_7, m_{10}. Control parameter n=0;

EVALUATION OF ON-LINE PULSE CONTROL FOR VIBRATION SUPPRESSION IN FLEXIBLE SPACECRAFT



Control parameters:

$n = 1$

$\check{c} = 1$

$T_d = 0.05$

$T_{min} = 0.2$

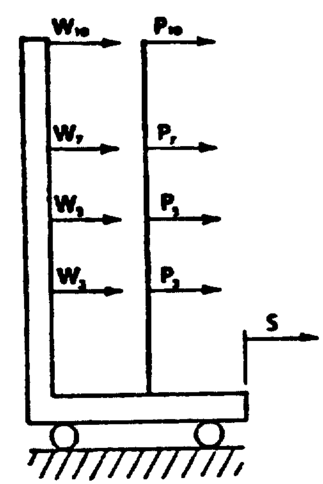
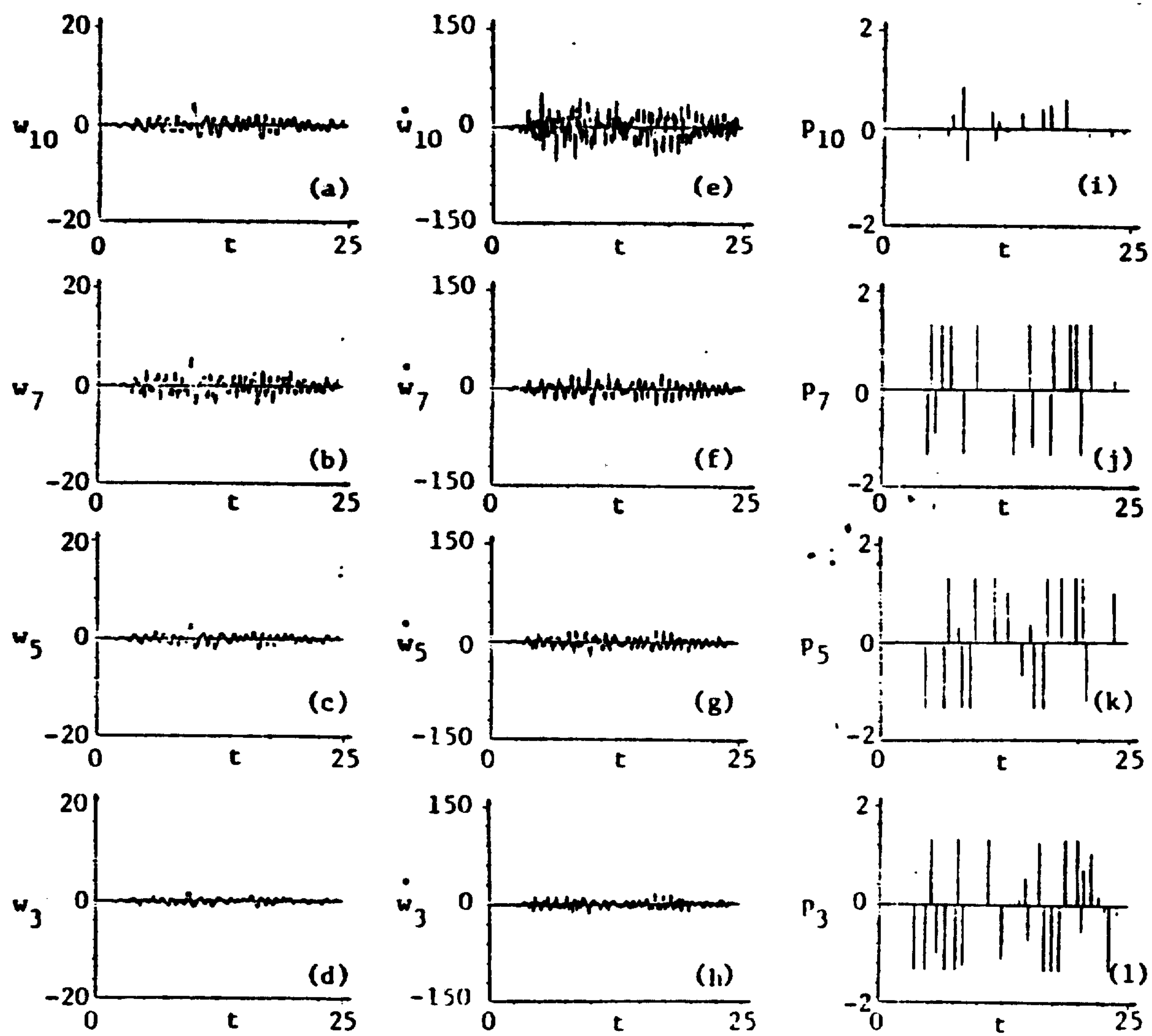


Figure 8. Controlled motion of the 10 DOF linear plate model under nonstationary base excitation; 4 identical controllers used at locations m_3, m_5, m_7, m_{10}. Control parameter n=1;

EVALUATION OF ON-LINE PULSE CONTROL FOR VIBRATION SUPPRESSION IN FLEXIBLE SPACECRAFT



Control parameters:

$n = 2$

$c = 1$

$T_d = 0.1$

$T_{min} = 0.2$

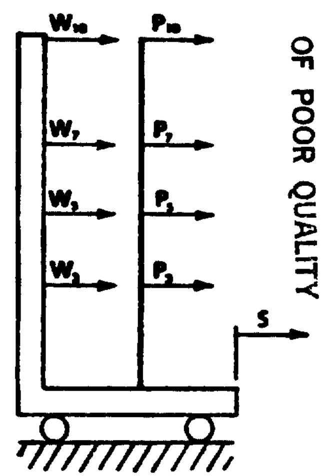


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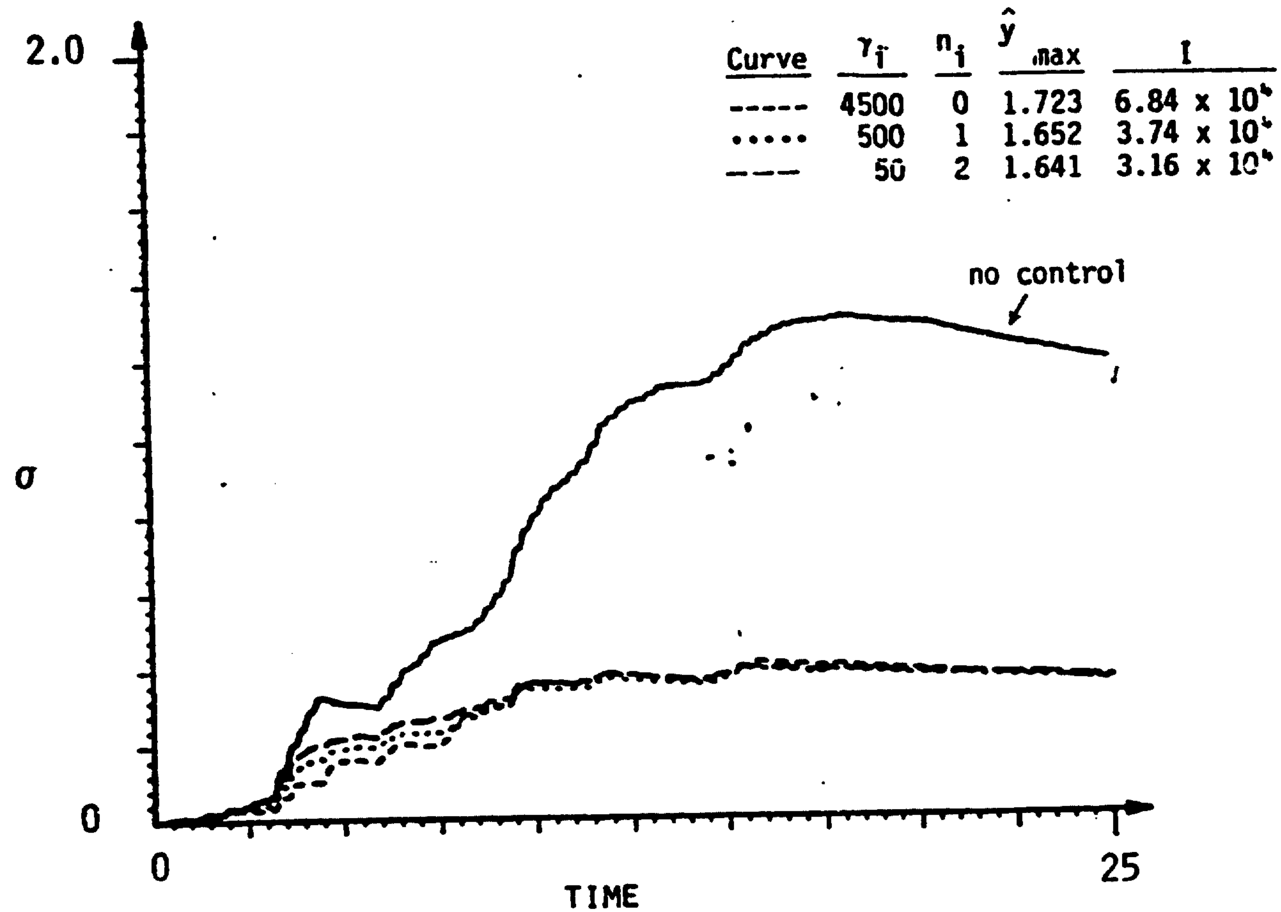
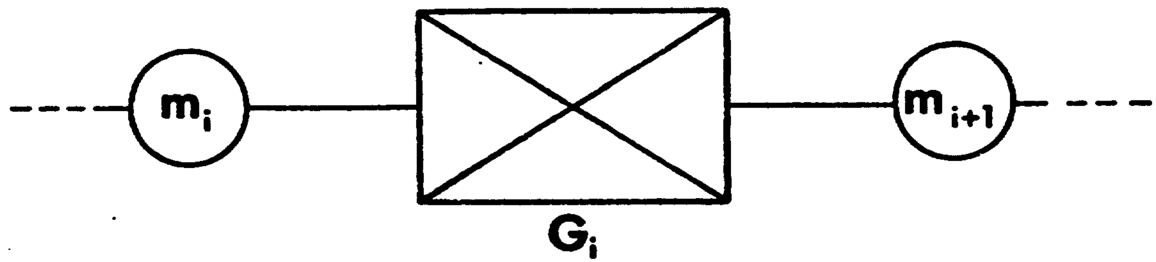
Figure 9. Controlled motion of the 10 DOF linear plate model under nonstationary base exictation; 4 identical controllers used at locations m_3, m_5, m_7, m_{10}. Control parameter n=2;

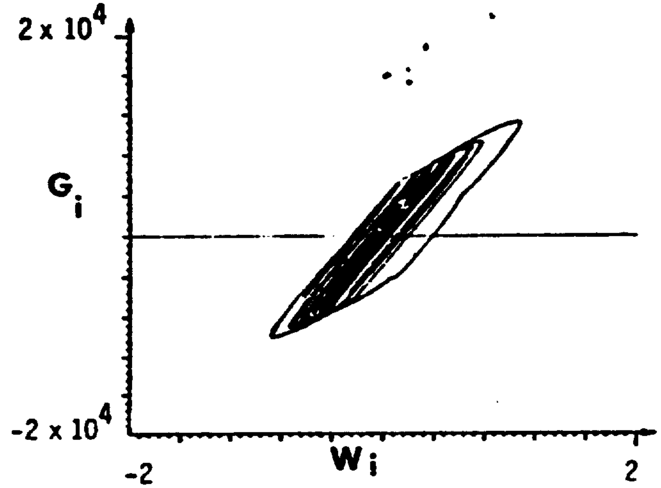
"Effects of Control Parameters"



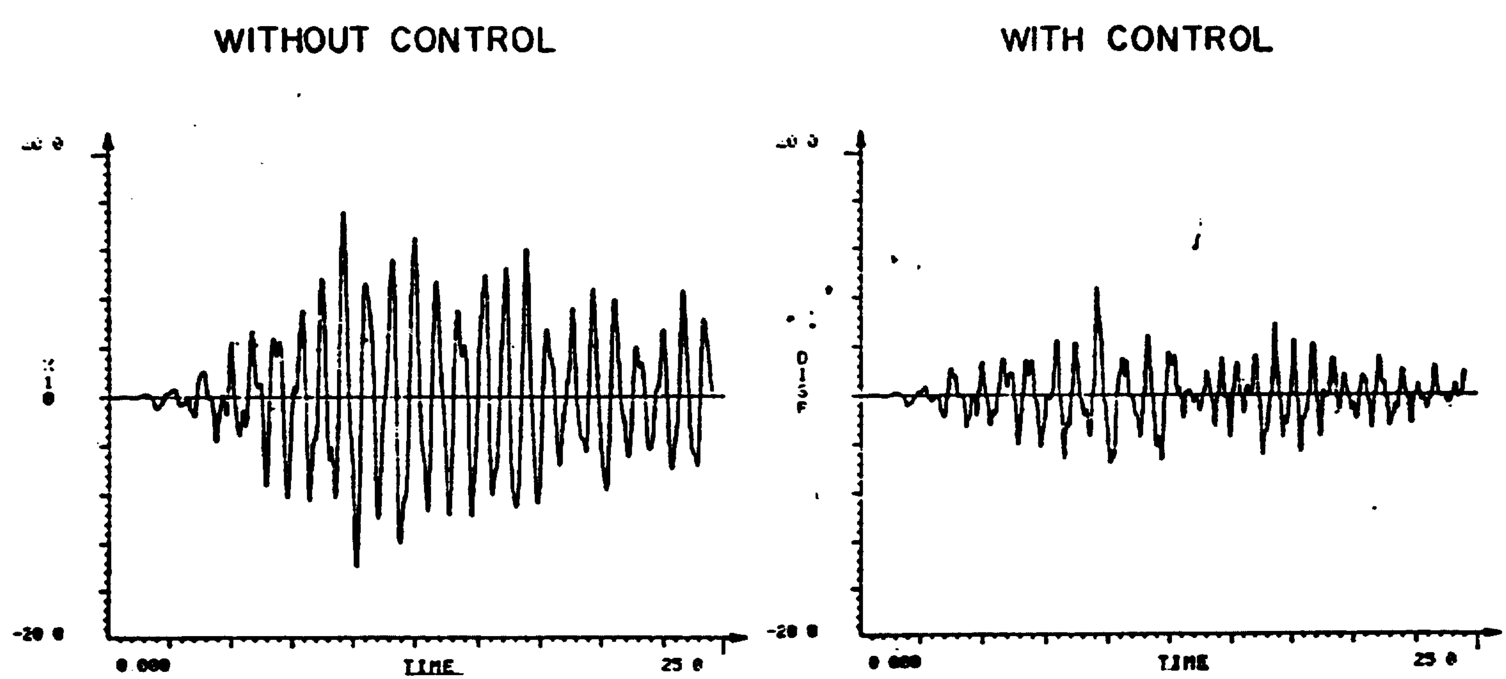
Comparison of RMS response with and without suboptimal active control.

"Response of a Nonlinear Flexible Structure"

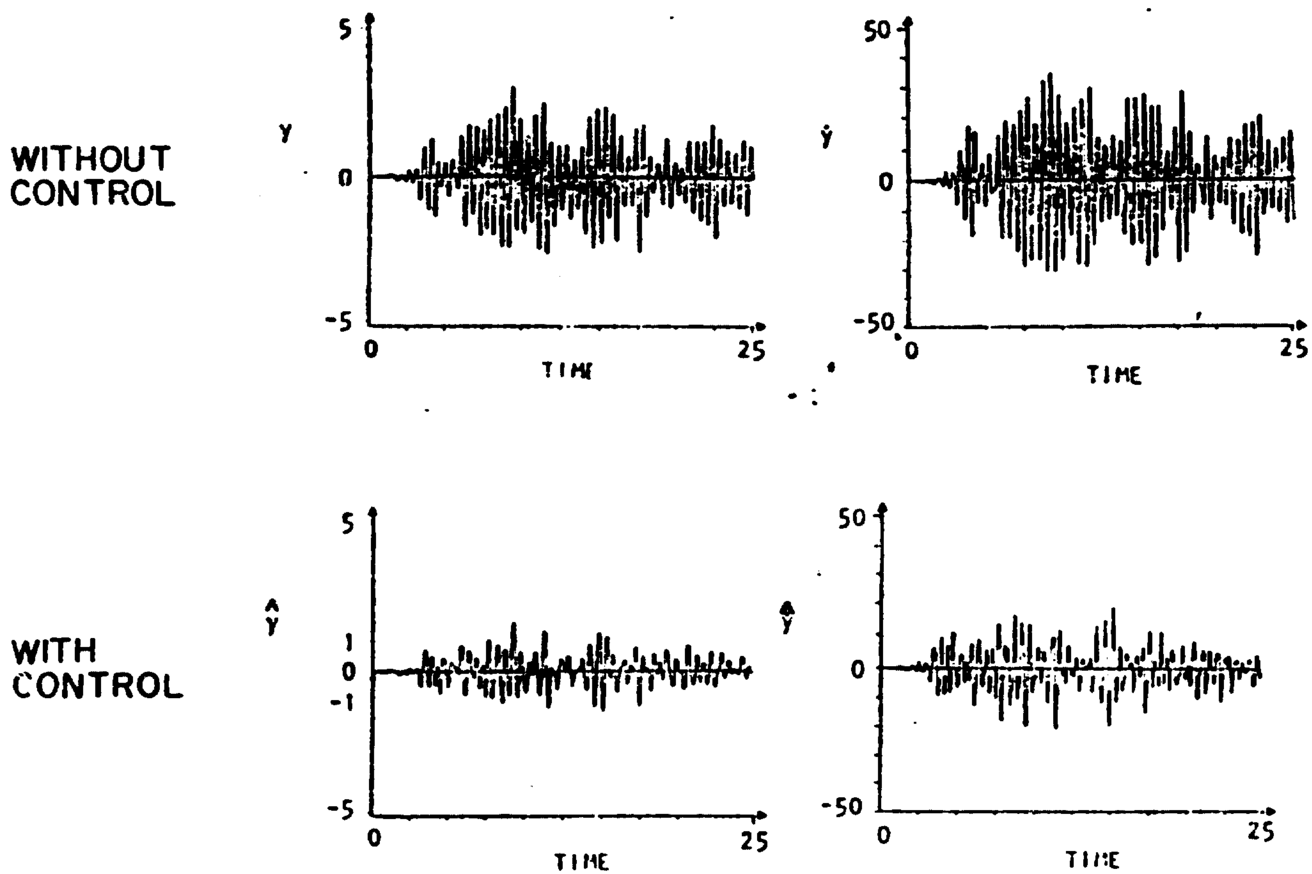




"Response of the Flexible Appendage to Base Excit."



"Response of a Nonlinear Flexible Structure"



EVALUATION OF ON-LINE PULSE CONTROL FOR VIBRATION SUPPRESSION IN FLEXIBLE SPACECRAFT

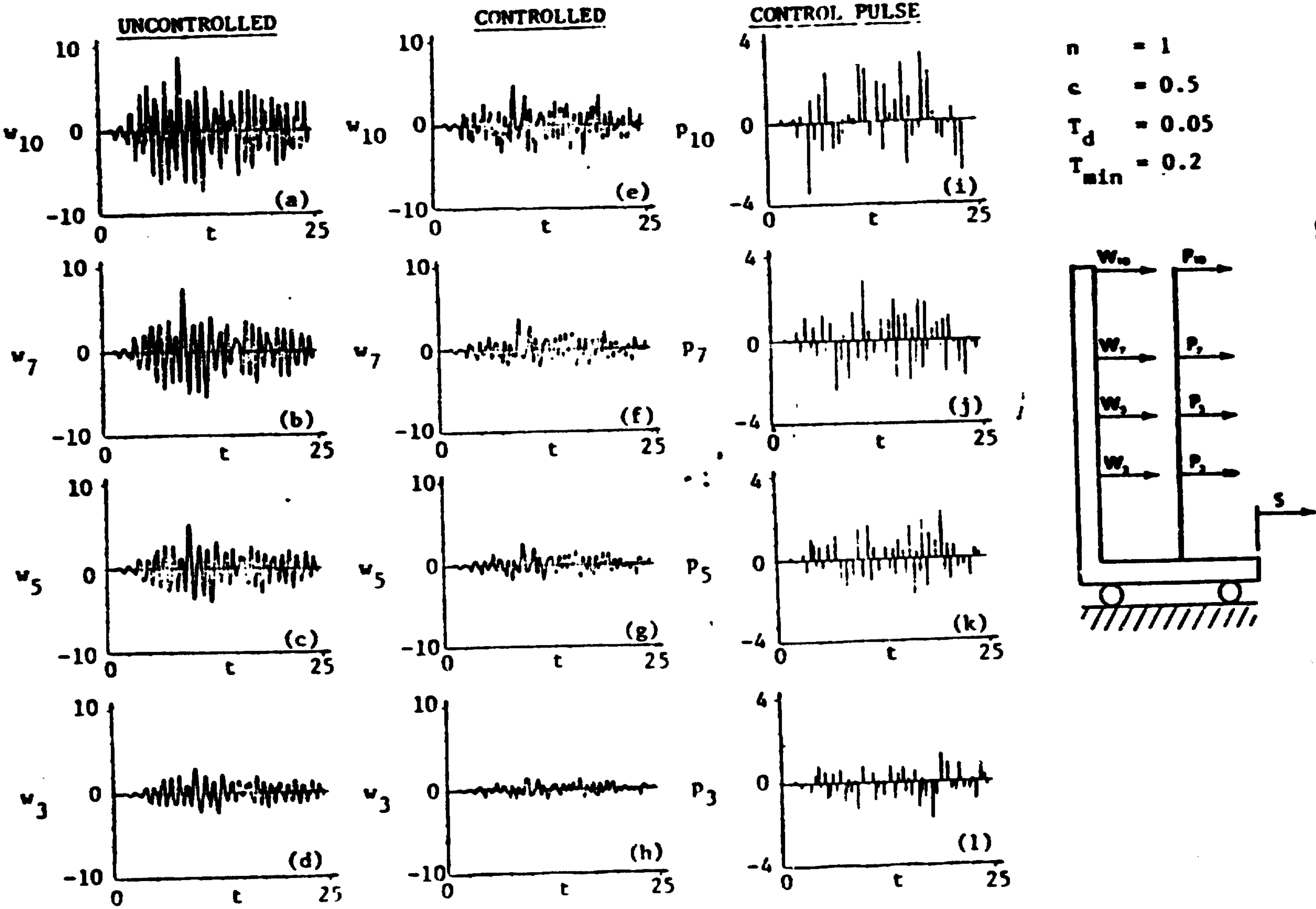


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Figure 13. Motion of a hysteretic 10 DOF nonlinear plate model under nonstationary base excitation; n = 1.

STABILITY ANALYSIS

Consider a controlled nonlinear dynamic system governed by:

$$M\ddot{\underset{\sim}{x}} + (D+2cM)\dot{\underset{\sim}{x}} + (K+2c^2M)\underset{\sim}{x} + \underset{\sim}{f}(\underset{\sim}{x},\dot{\underset{\sim}{x}}) + \nabla F(\underset{\sim}{x}) + \underset{\sim}{g}(\dot{\underset{\sim}{x}}+c\underset{\sim}{x}) = \underset{\sim}{q}(t)$$

where the control force is given by:

$$\underset{\sim}{h}(\dot{\underset{\sim}{x}}+c\underset{\sim}{x}) = -2cM(\dot{\underset{\sim}{x}}+c\underset{\sim}{x}) - \underset{\sim}{g}(\dot{\underset{\sim}{x}}+c\underset{\sim}{x})$$

and c is a positve constant and

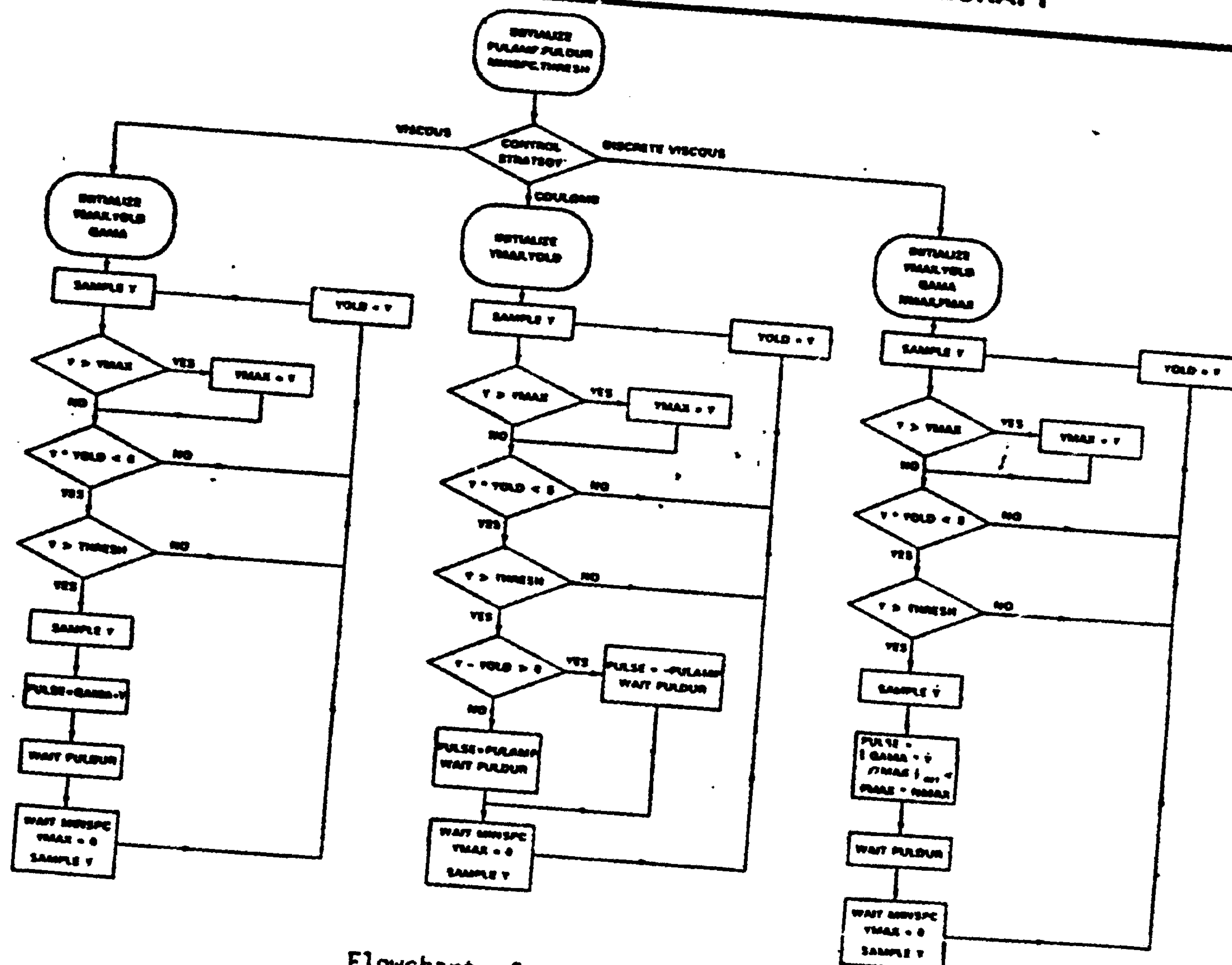
$$(\dot{\underset{\sim}{x}}+c\underset{\sim}{x})^T\underset{\sim}{g}(\dot{\underset{\sim}{x}}+c\underset{\sim}{x}) \geq 0 \;.$$

Using Liapunov's direct method, the authers have shown that the solutions of the equations of motion are Lagrange stable (bounded).

ANALOG STUDIES

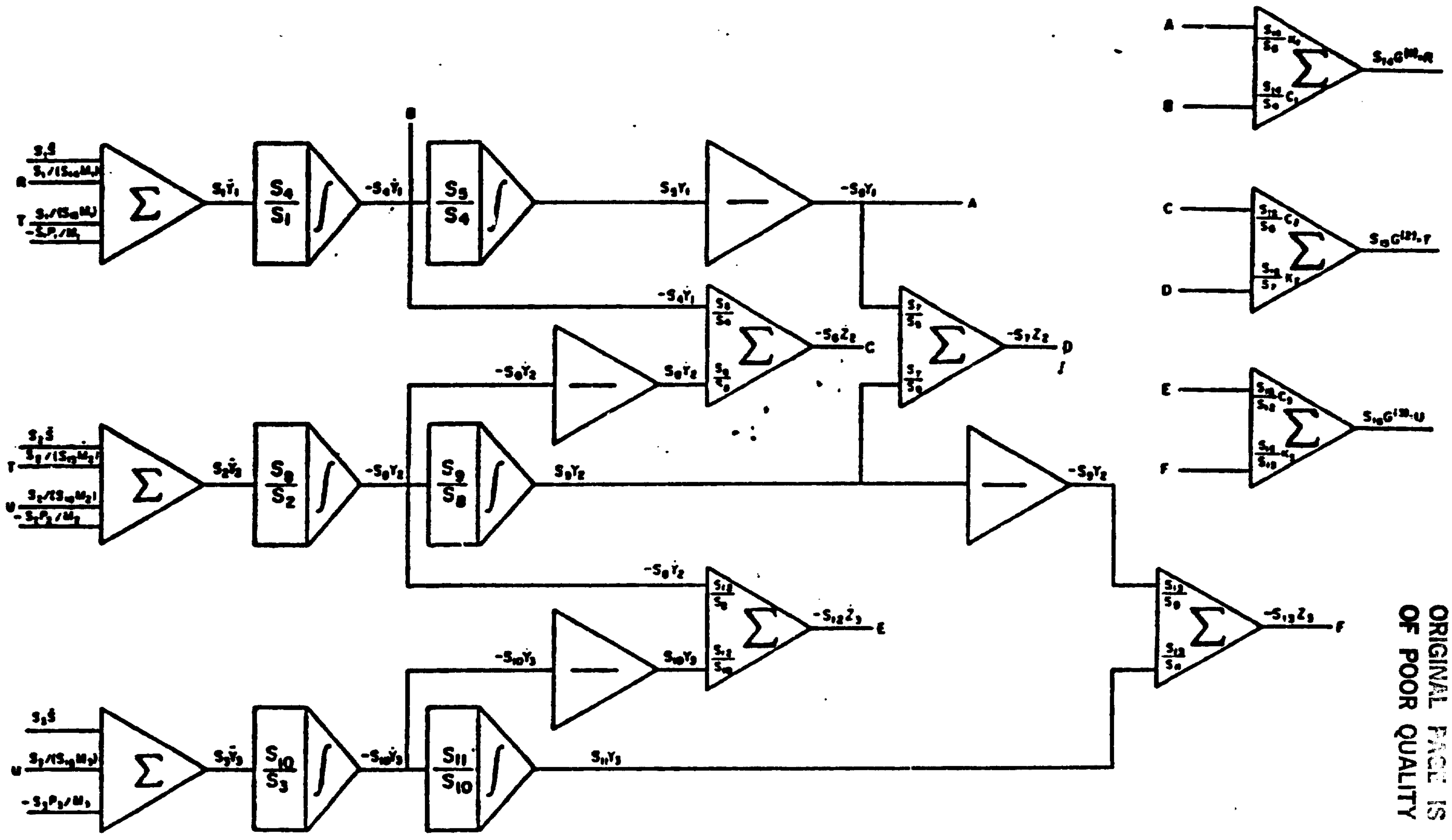
* D/A and A/D conversions
* On-Line implementation
* Time-lag robustness

EVALUATION OF ON-LINE PULSE CONTROL FOR VIBRATION SUPPRESSION IN FLEXIBLE SPACECRAFT



Flowchart of the active pulse control strategy.

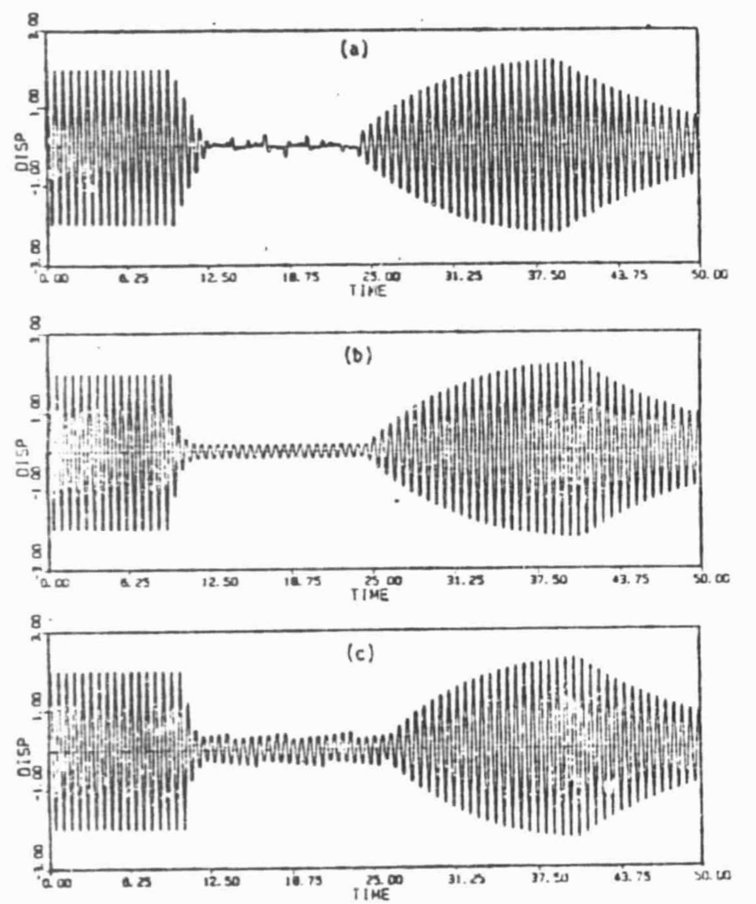
EVALUATION OF ON-LINE PULSE CONTROL FOR VIBRATION SUPPRESSION IN FLEXIBLE SPACECRAFT



Analog computer circuit

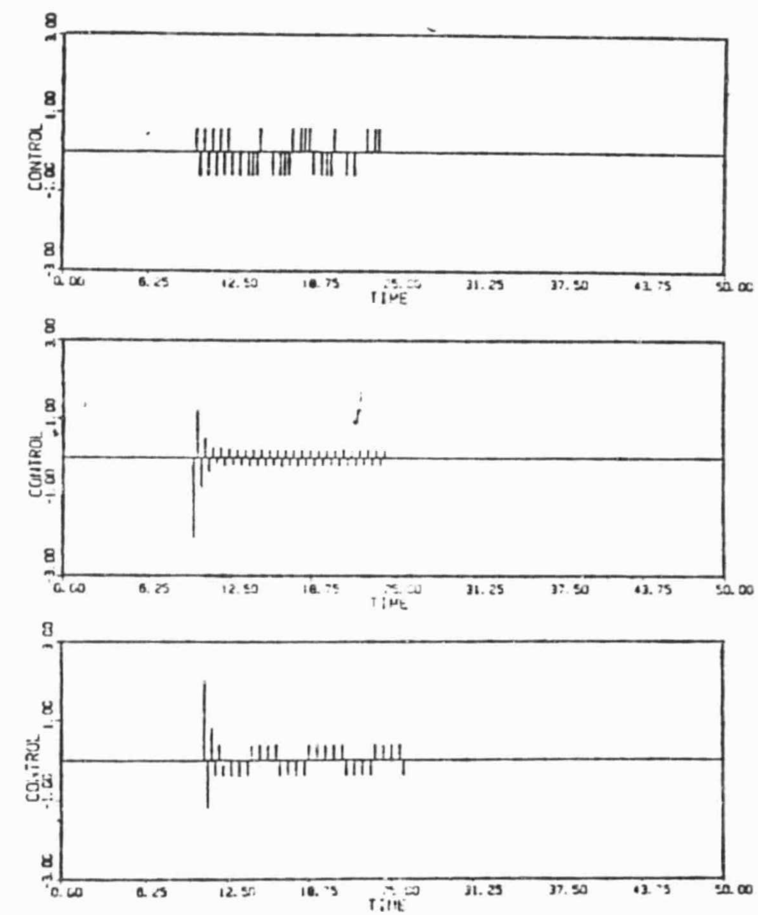
EVALUATION OF ON-LINE PULSE CONTROL FOR VIBRATION SUPPRESSION IN FLEXIBLE SPACECRAFT

PULSE DURATION = 50 msec PULSER LOCATION = (0, 0, 1)



Effects of control parameters on the analog simulated response
(a) Coulomb control, γ_3 = 4800, n_3 = 0; (b) viscous control, γ_3 = 600, n_3 = 1; (c) discretized viscous control, γ_3 = 600, n_3 = 1, number of ON/OFF pulsers = 3.

PULSE DURATION = 50 msec PULSER LOCATION = (0, 0, 1)



Effects of control parameters on the pulse amplitudes used to control the response (a) Coulomb control, γ_3 = 4800, n_3 = 0; (b) viscous control, γ_3 = 600, n_3 = 1; (c) discretized viscous control, γ_3 = 600, n_3 = 1, number of ON/OFF pulsers = 3.

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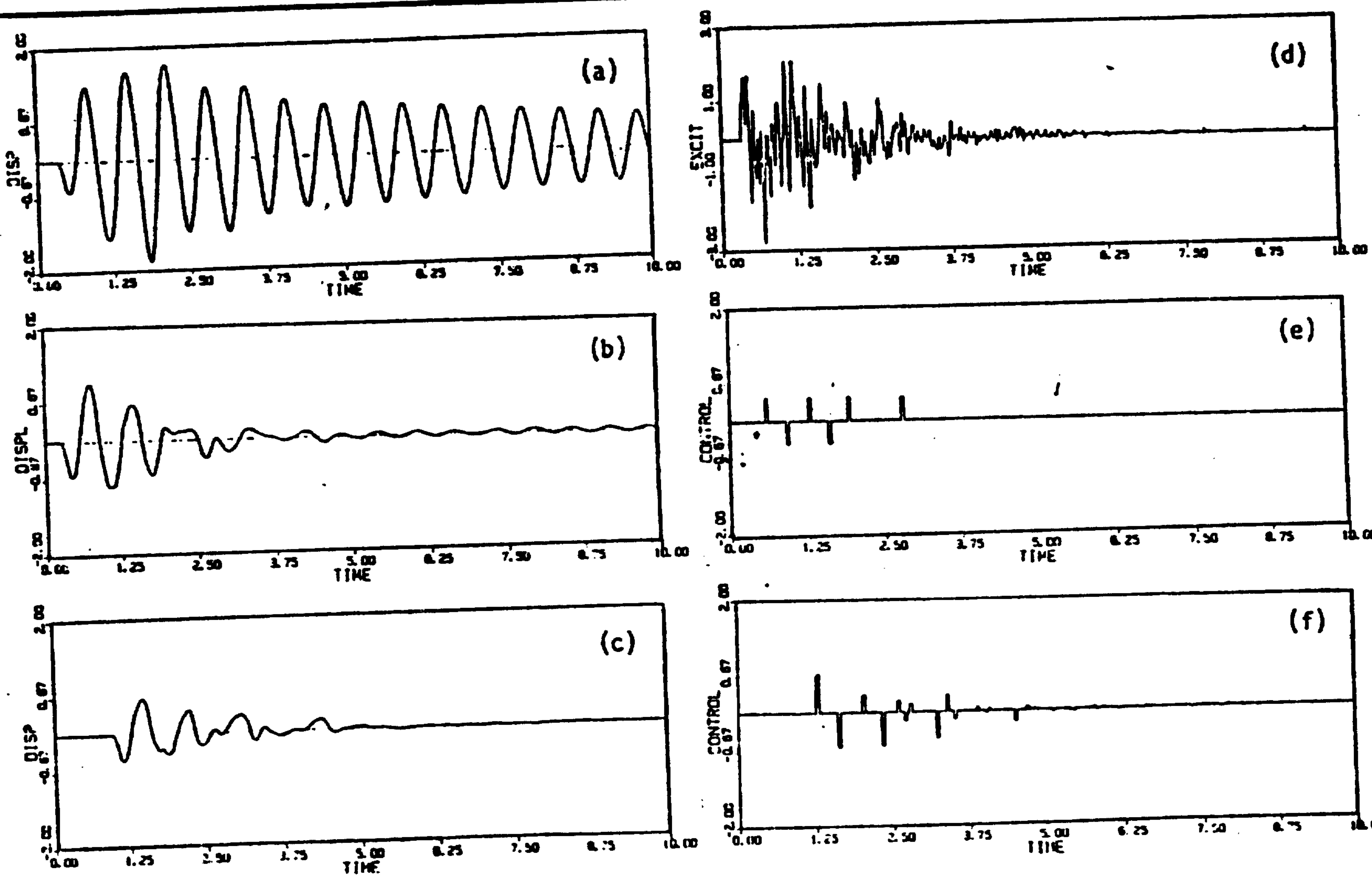
EVALUATION OF ON-LINE PULSE CONTROL FOR VIBRATION SUPPRESSION IN FLEXIBLE SPACECRAFT



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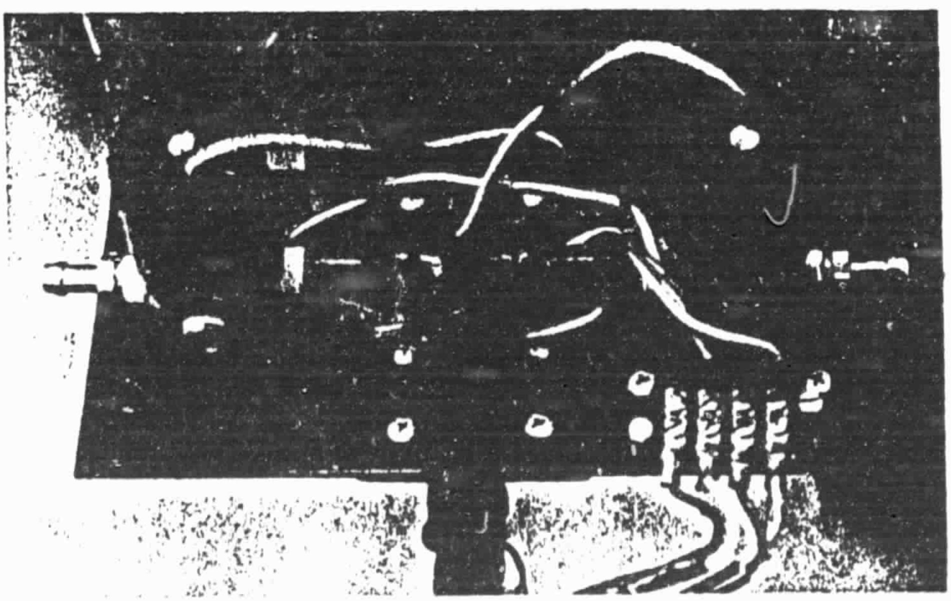
Analog computer response
(a) uncontrolled displacement, (b) controlled displacement, $\gamma = 4800$, $n = 0$;
(c) controlled displacement. $\gamma = 600$, $n = 1$.

EXPERIMENTAL STUDIES

* Mechanical model resembling an Aircraft Wing
* Electrodynamic Shaker at Base
* 2 Inexpensive Control Jets at Top

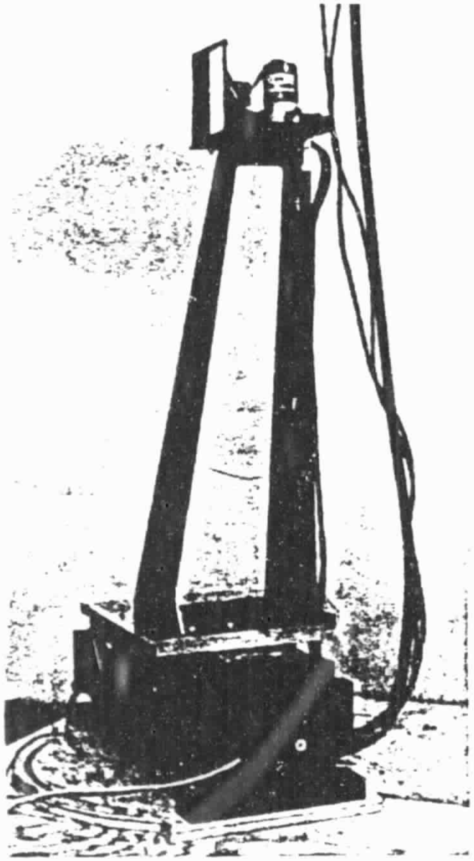
(a) Base-excited plate

(b) Solenoid

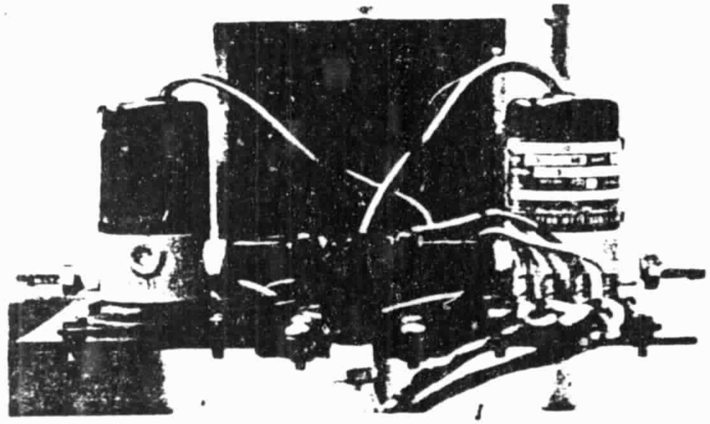


(c) Reaction-jet controllers

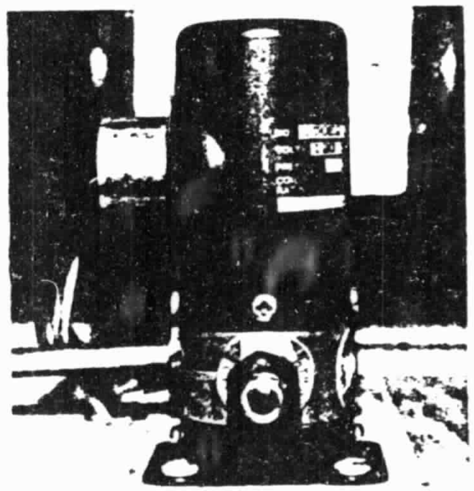
"Photographs of the Experimental Set-up"



TEST STRUCTURE & EXCITER

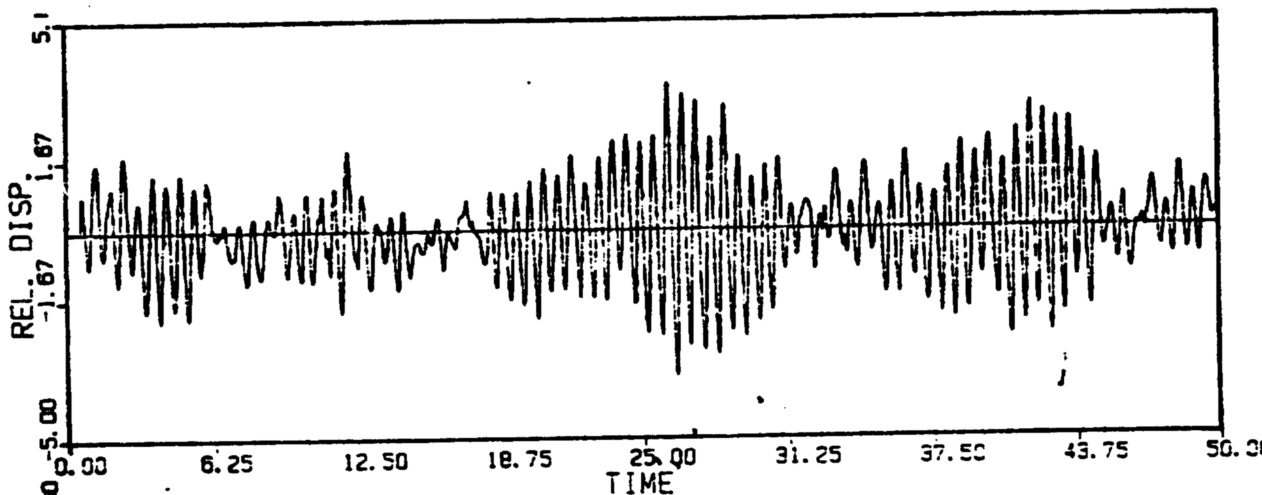


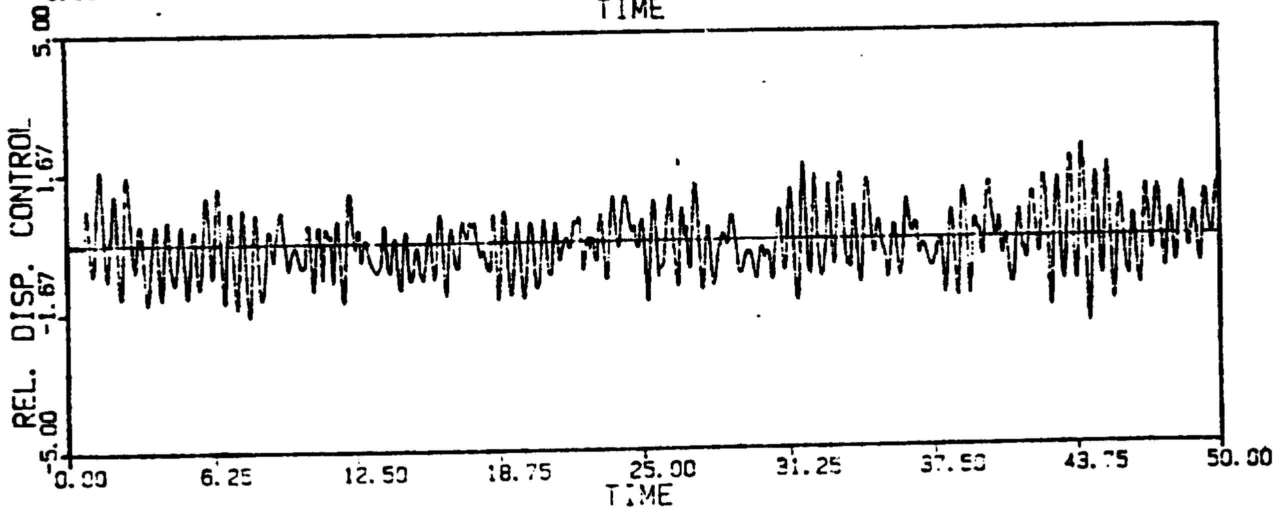
CONTROL ASSEMBLY



PNEUMATIC THRUSTER

"Experimental Studies of the Flexible Appendage"





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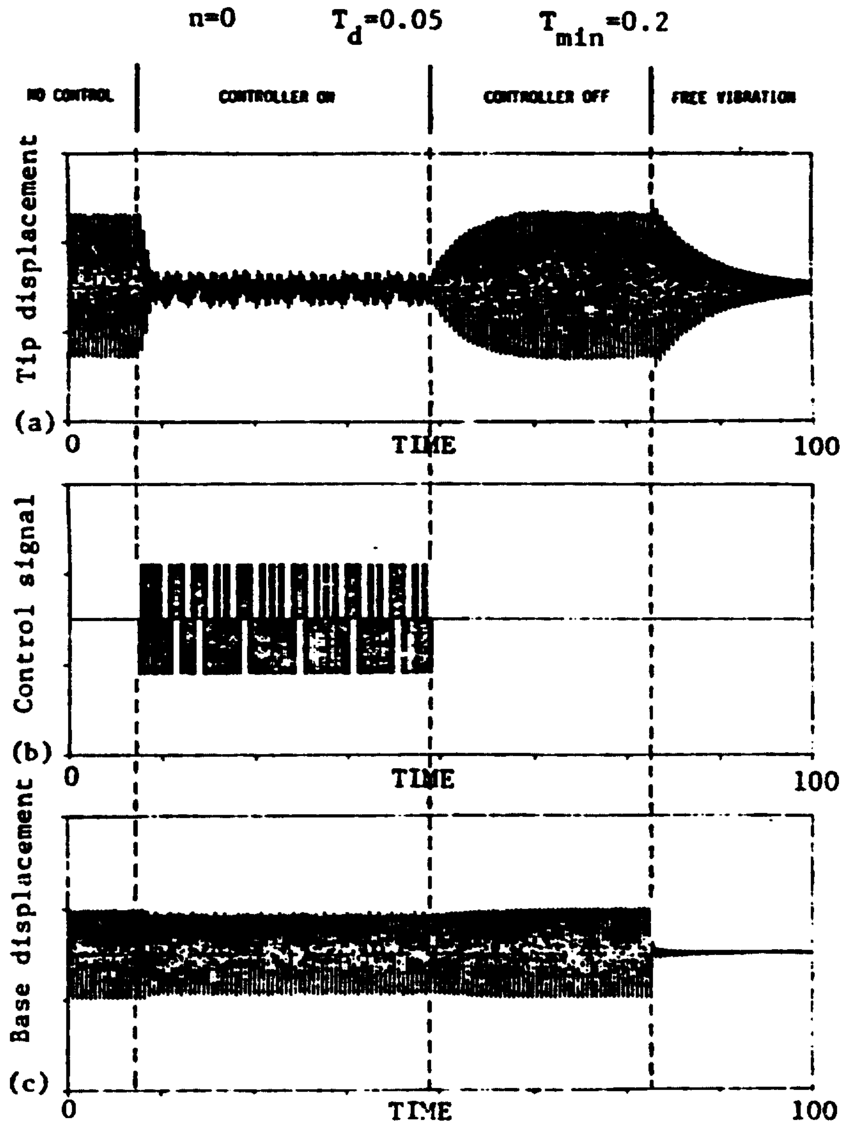
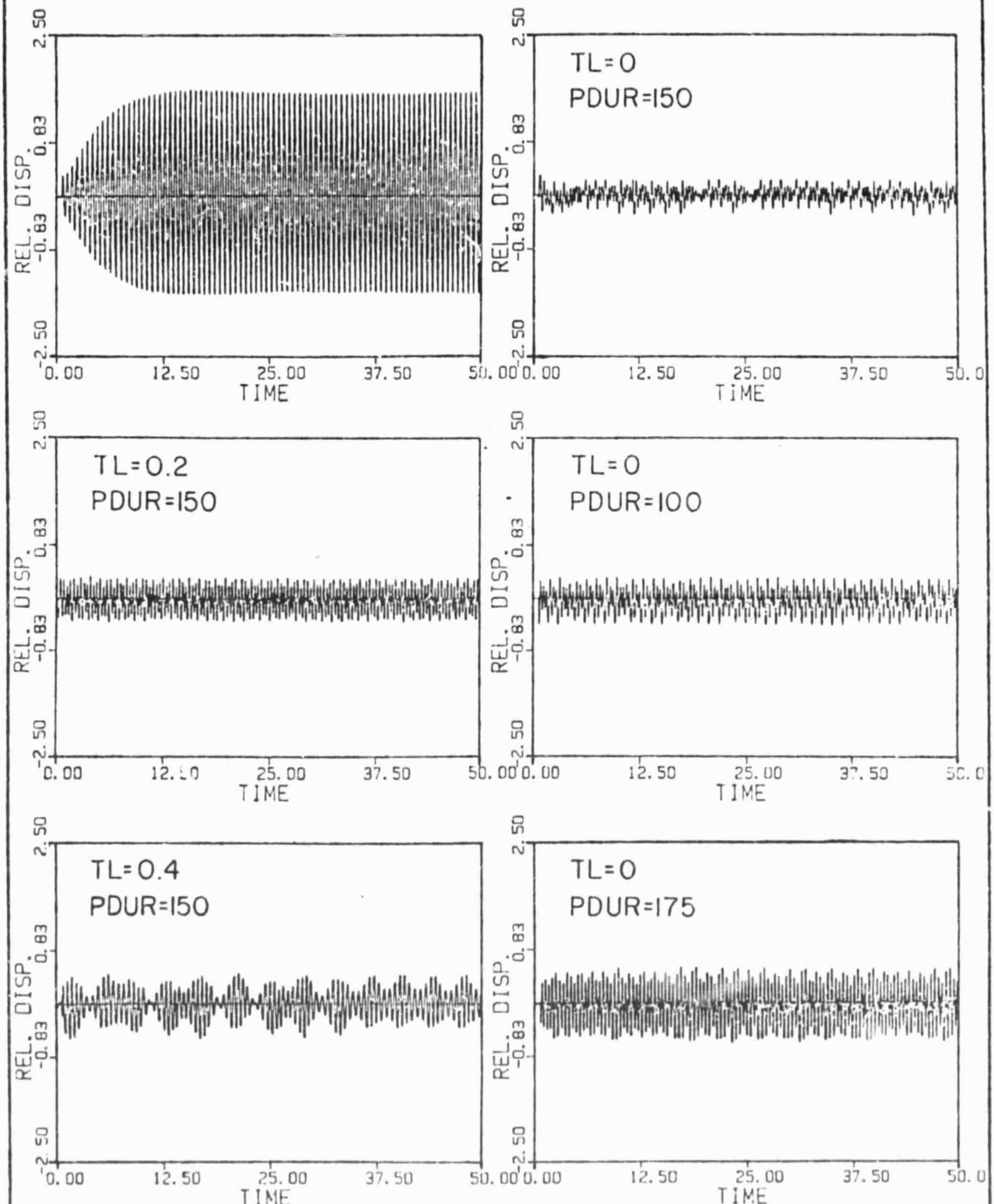
EVALUATION OF ON-LINE PULSE CONTROL FOR VIBRATION SUPPRESSION IN FLEXIBLE SPACECRAFT

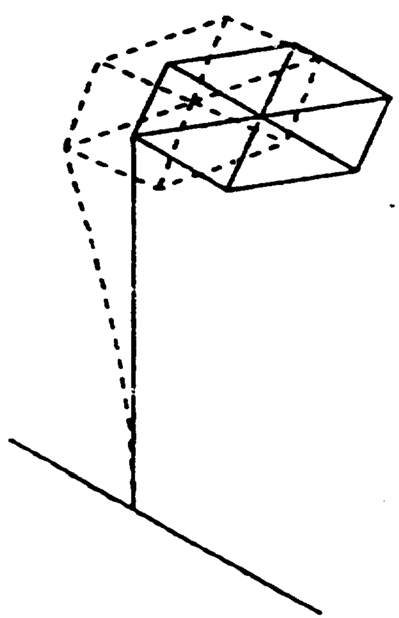


Measured response of plate with and without harmonic base excitation; one controller used at top of plate.

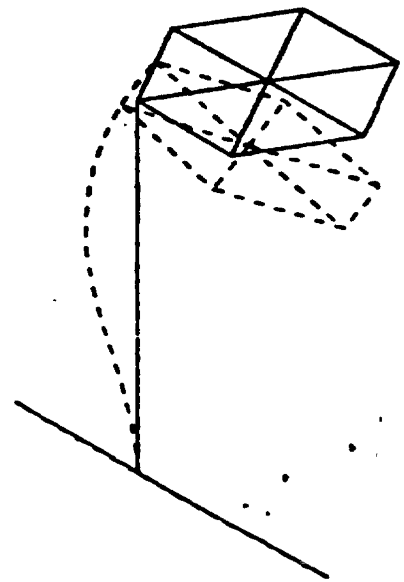
"Experimental Studies of the Flexible Appendage "



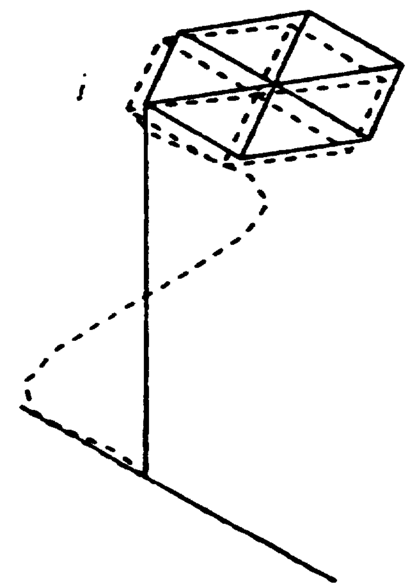
EVALUATION OF ON-LINE PULSE CONTROL FOR VIBRATION SUPPRESSION IN FLEXIBLE SPACECRAFT



MODE SHAPE 1 FREQUENCY 1.901E+00

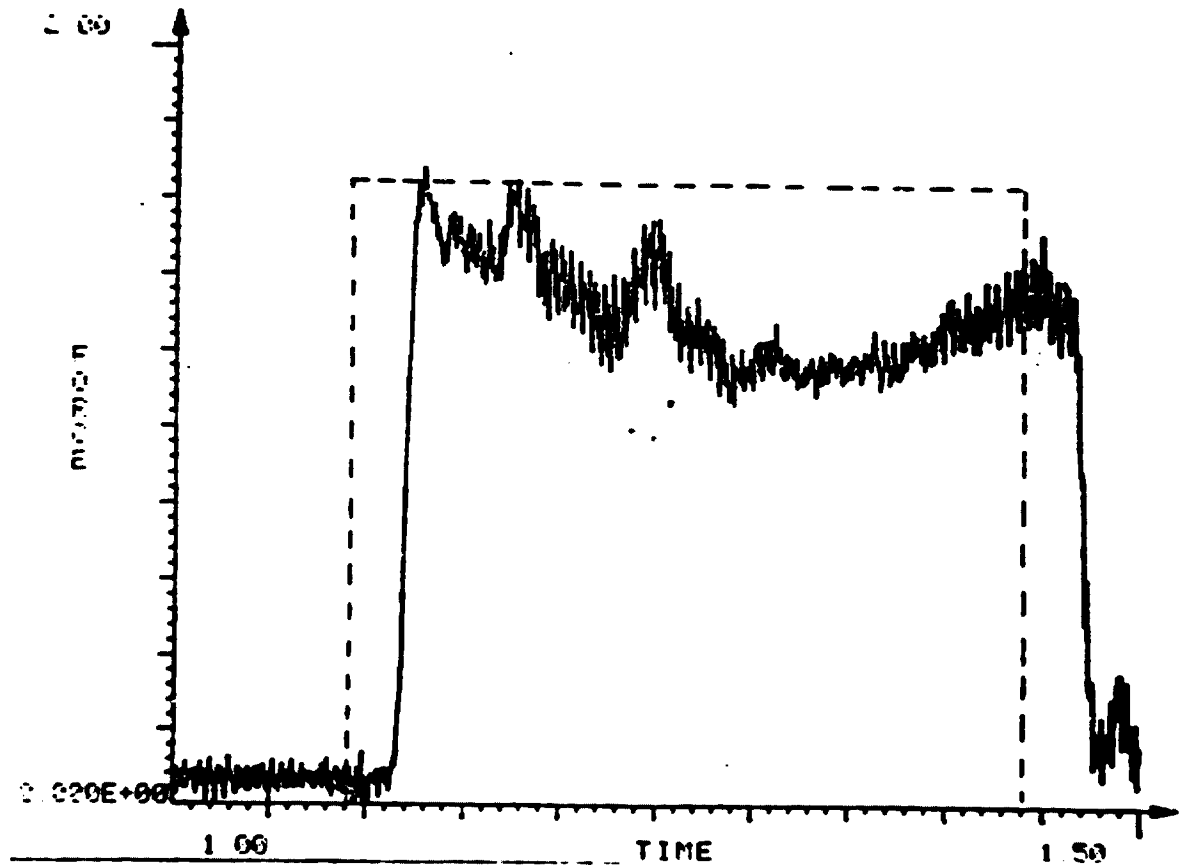


MODE SHAPE 3 FREQUENCY 8.816E+00



MODE SHAPE 7 FREQUENCY 8.360E+01

EVALUATION OF ON-LINE PULSE CONTROL FOR VIBRATION SUPPRESSION IN FLEXIBLE SPACECRAFT



EVALUATION OF ON-LINE PULSE CONTROL FOR VIBRATION SUPPRESSION IN FLEXIBLE SPACECRAFT